Low-Noise Propeller Design with the Vortex Lattice Method

Preliminary Results

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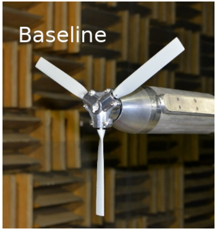
Motivation: noise will be a limiting factor for UAM/AAM concepts

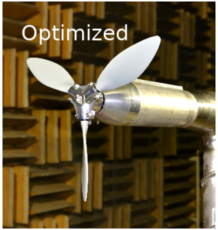
Previous Work: BEMT+Compact F1A+Optimization=Quiet Propeller

Combined

- a propeller aerodynamic code, implementation of blade element momentum theory (BEMT)
- a propeller acoustic code, implementation of the compact form of Farrasat's 1A acoustic analogy
- gradient-based optimization

to design an optimally efficient propeller subject to thrust and acoustic constraints.





Current Goal: `s/BEMT/VLM/g`

- Blade Element Momentum Theory is great
  - fast
  - robust
  - accurate for “simple” cases (isolated propeller, on axis flow)

  but **limited in applicability** (multiple rotors, installation effects, off-axis flow, etc.)
- CFD too slow for highly multi-disciplinary optimizations

Goal

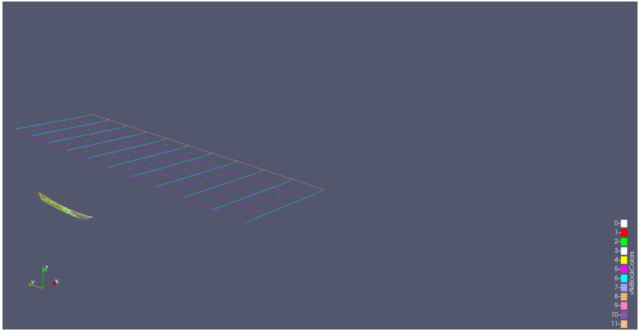
Replace the BEMT aerodynamic model used in previous work with the vortex lattice method (VLM)

How?

- Aerodynamics: VortexLattice.jl, unsteady vortex lattice method (VLM) from T. McDonnell and A. Ning (BYU)
- Acoustics: AcousticAnalogies.jl, compact form of Farassat's formulation 1A (incl. compact monopole approximation from L. Lopes)
- Optimizer: SNOPT, via SNOW.jl, nonlinear gradient-based optimizer

VLM from VortexLattice.jl, Taylor McDonnell and Andrew Ning, BYU

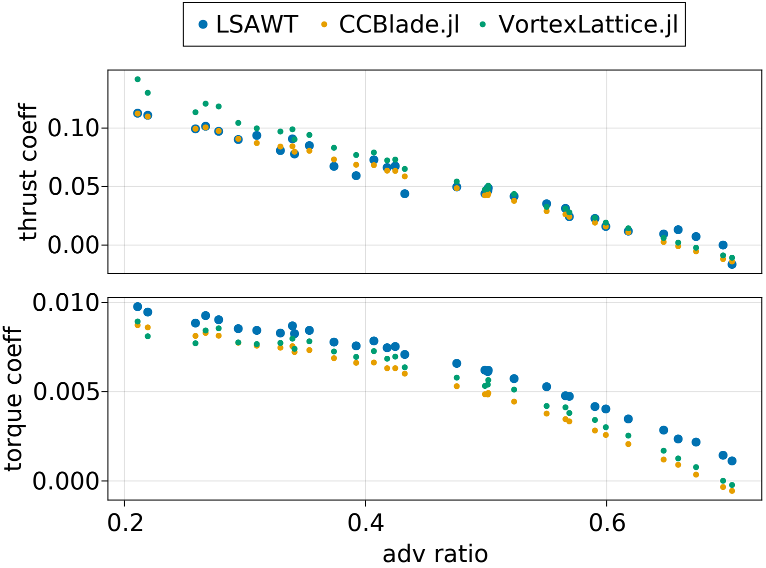
- unsteady
- free wake
- viscous loading model
- Prandtl-Glauert compressibility correction
- **compatible with automatic differentiation (AD) libraries**
- great docs
- great examples
- open source



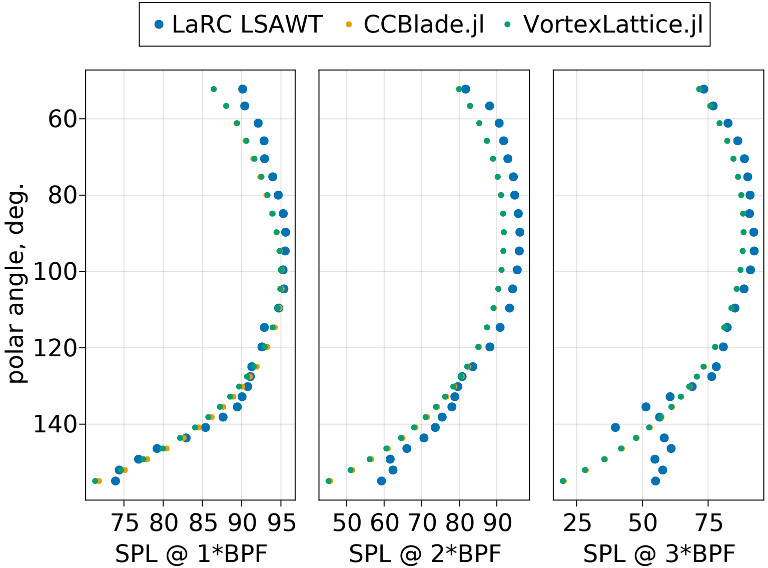
Results will be compared to a baseline design from Zawodny, Lopes, NASA LaRC

- 24 inch diameter
- 3 blades
- Constant 1.5 inch chord
- Helical twist distribution
- NACA 0012 airfoil sections throughout
- Tested in NASA LaRC's low speed acoustic wind tunnel (LSAWT).
- Aerodynamic and acoustic data available.

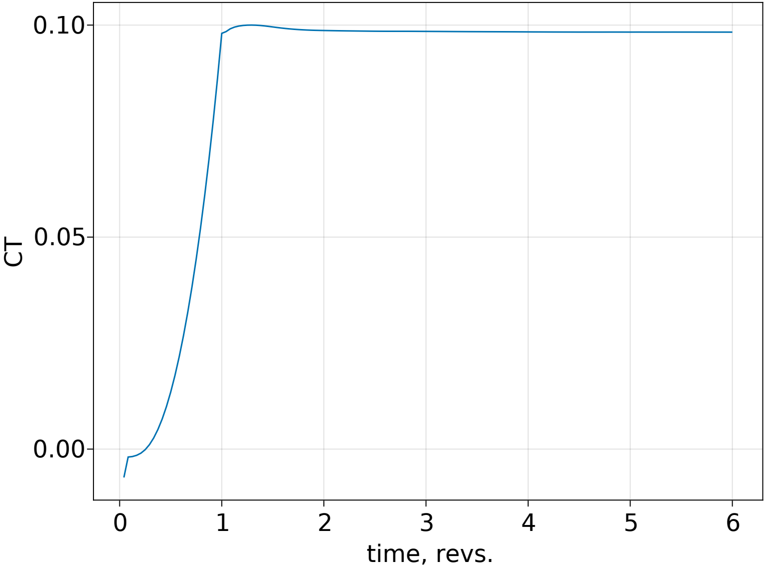
Comparison to LaRC LSAWT aero data looks pretty good



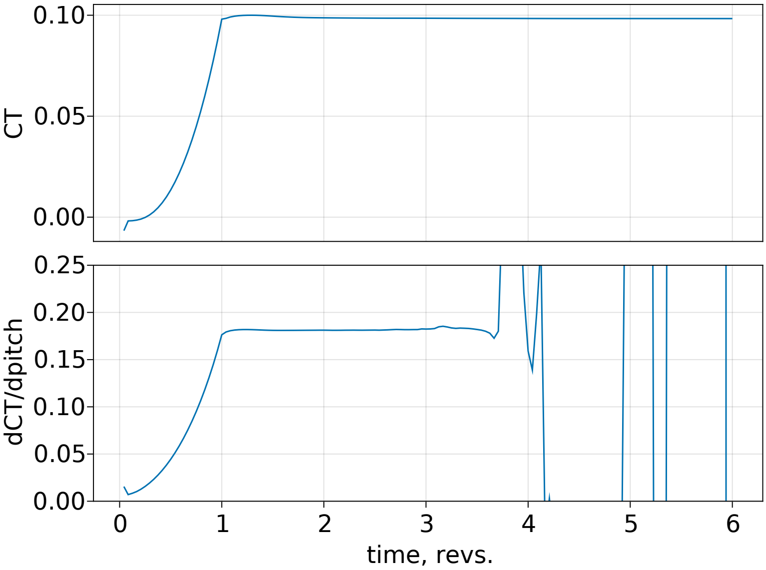
Comparison to LaRC LSAWT acoustic data looks pretty good



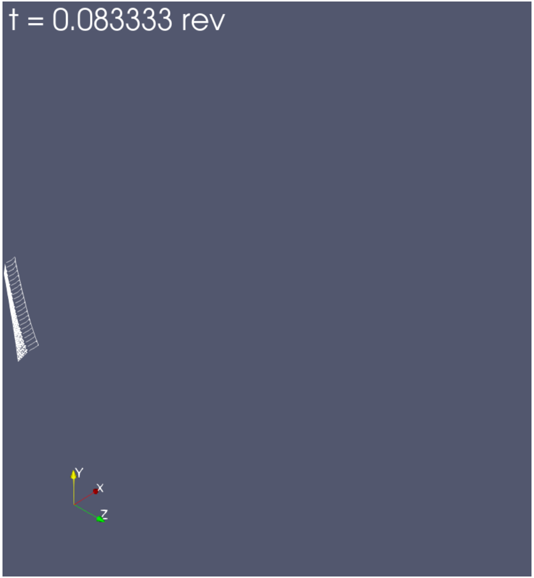
Need to make sure VLM outputs are smooth



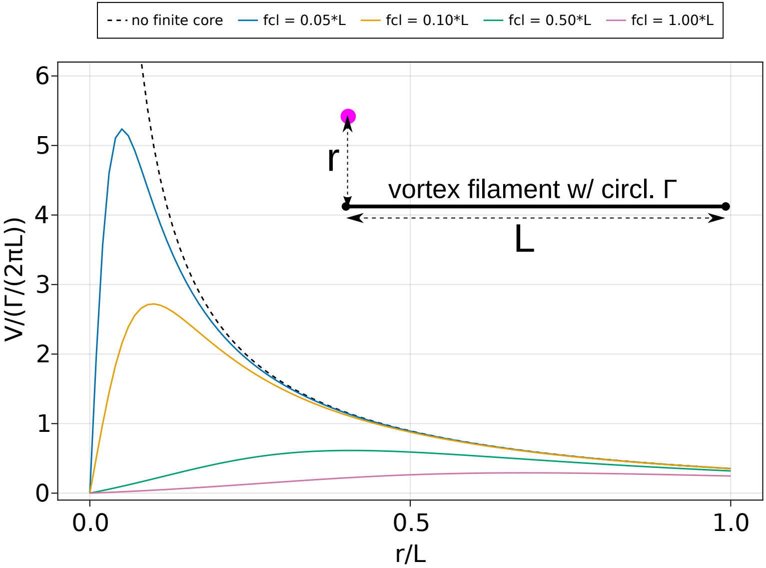
What about $\frac{\partial CT}{\partial \text{pitch}}$? Uh oh...



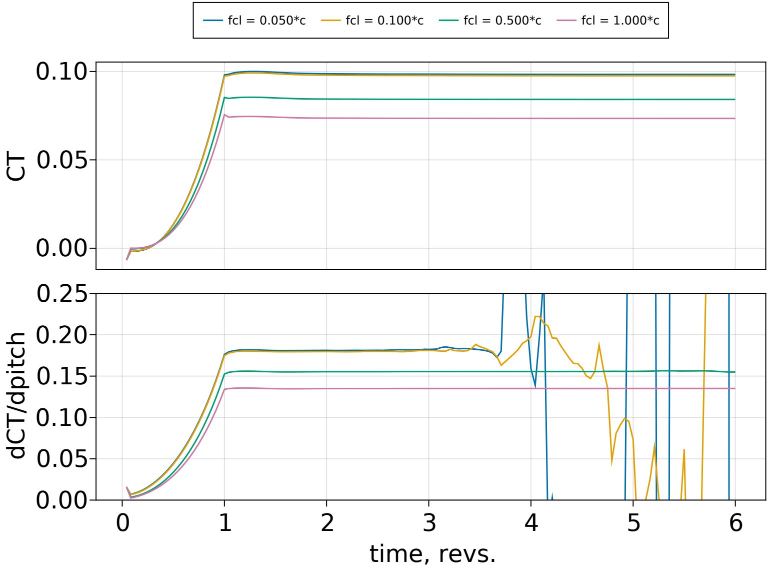
Lots of “twisting” at the downstream portion of the wake



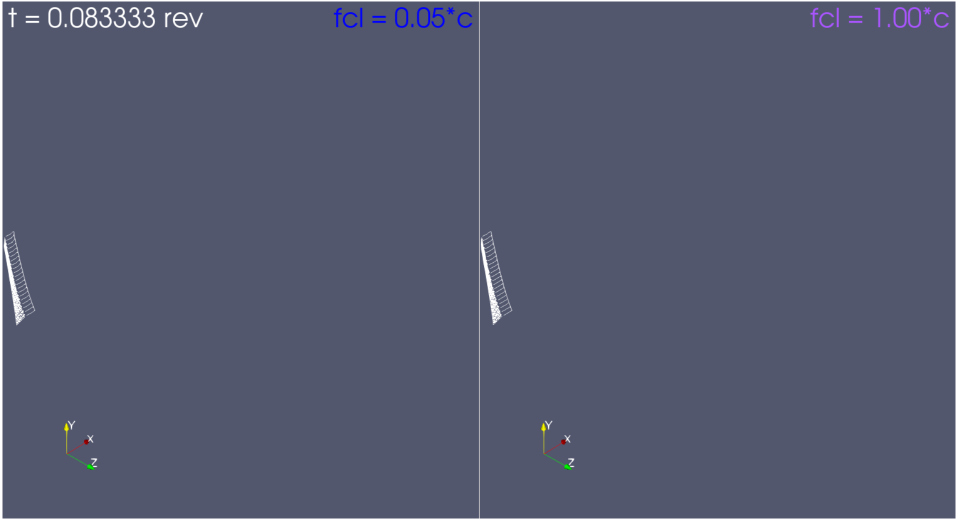
Finite core model tames the Biot-Savart law



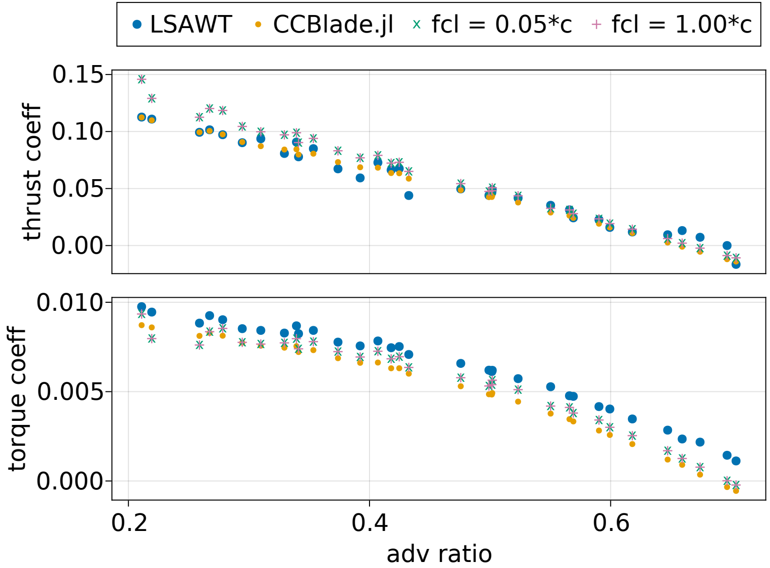
Tip #1: Finite core model helps VLM derivatives



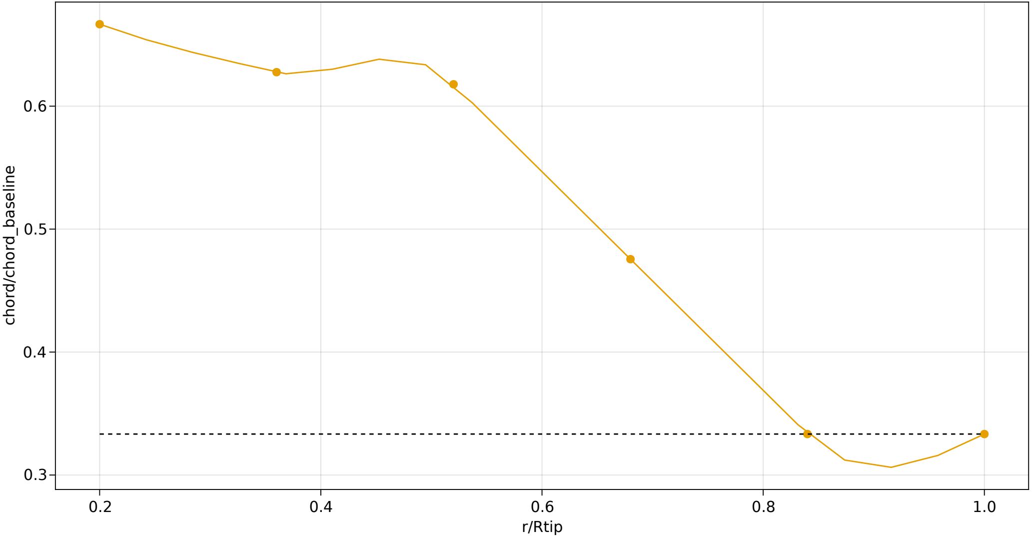
Effect of the finite core length on the wake trajectory is obvious



Increasing the finite core length doesn't spoil the predictions



Tip #2: Chord concavity constraint $\frac{d^2c}{dr^2} < 0$ helps



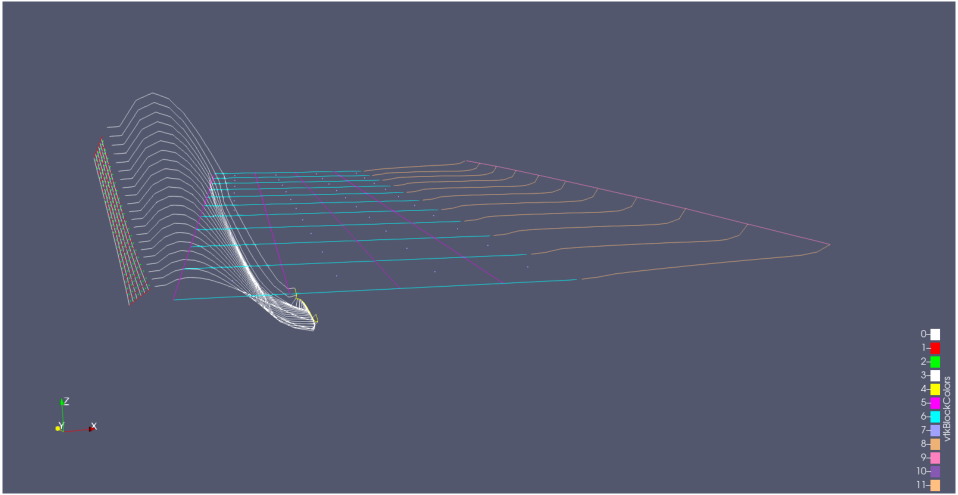
Propeller-Wing Configuration

- Wing geometry:
  - Four propeller radii long, wing chord is 1 propeller radius
  - $\approx 1/2$ propeller radii offset from propeller rotation axis
  - Wing leading edge $\approx 1/4$ propeller radii from propeller trailing edge
  - Wing at 4° angle of attack, propeller still aligned with freestrem
- Not capturing any noise associated with the unsteady loading **on the wing**, nor any reflections of the propeller's noise off the wing

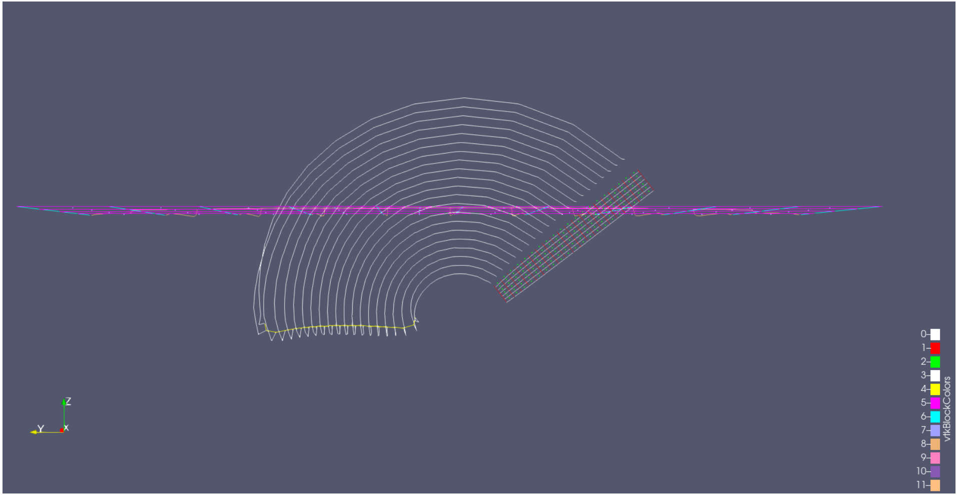
Goal

Disturb propeller inflow velocity, increasing noise and giving the optimizer something different to deal with

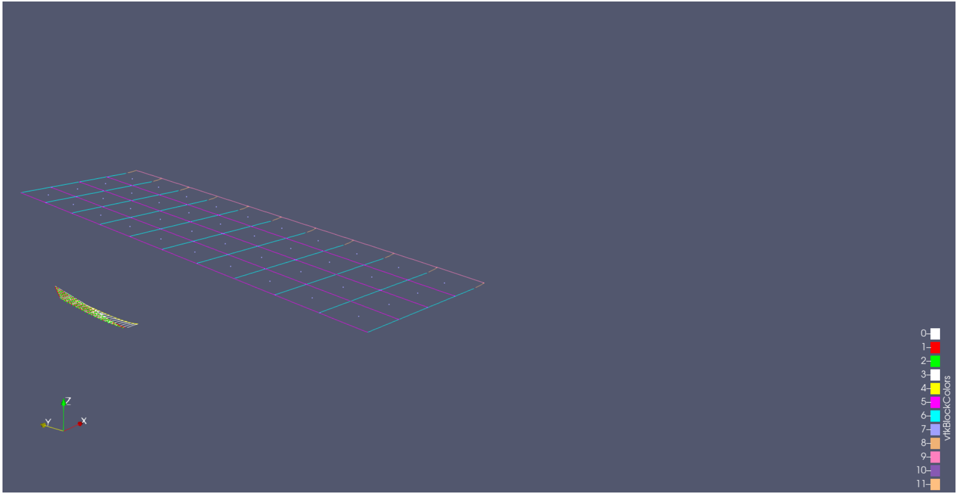
Wing is pretty close to the blade



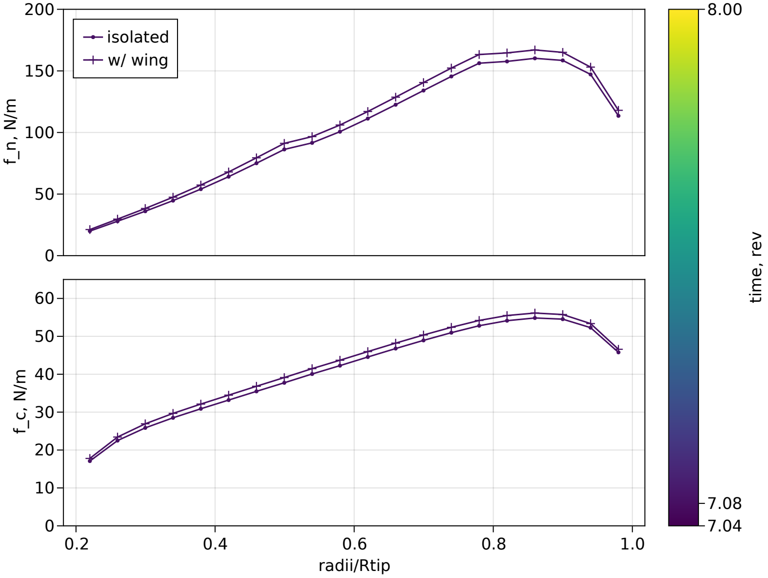
Blade passes by wing leading edge at about 1/2 span



Blade wake influences wing wake and vice versa



Noticeable change in loading distribution

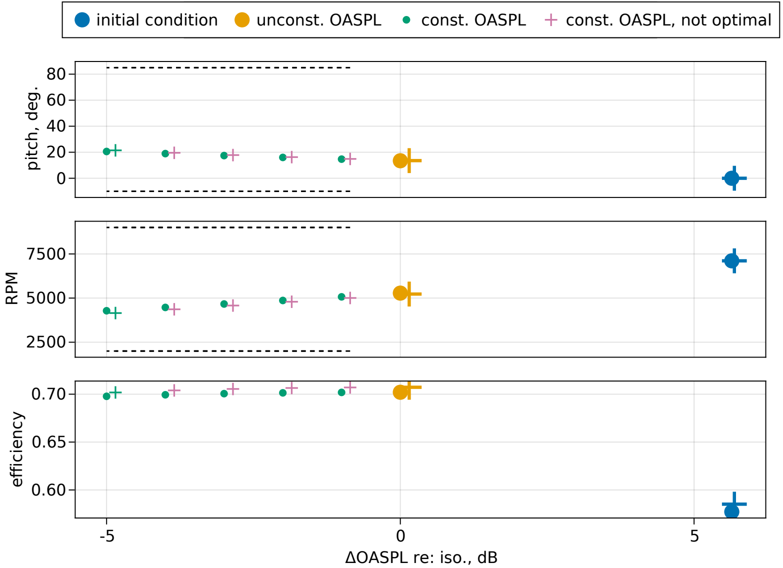


Results

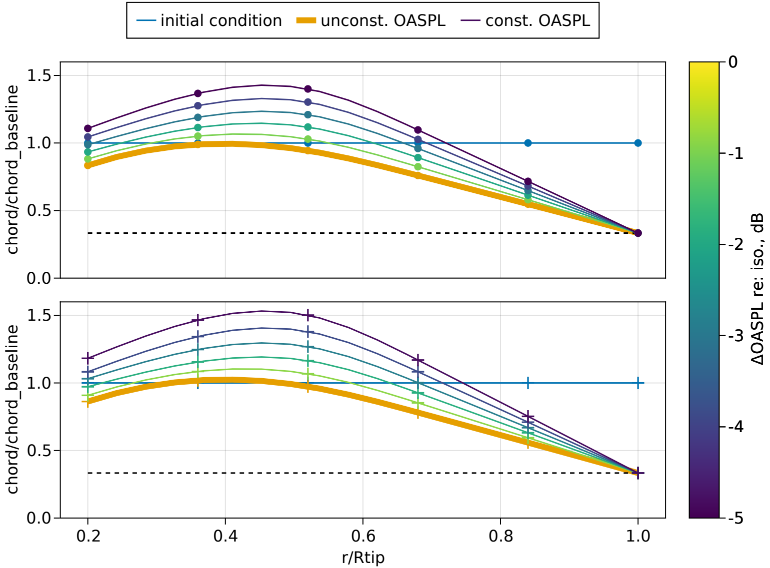
Problem setup

- Objective
  - **maximize efficiency** at cruise (Mach $= 0.11$ freestream)
- Design variables
  - **chord** distribution via 6 spline control points
  - **pitch** (aka collective) angle
  - **RPM**
- Constraints
  - **thrust** equal to baseline design's value
  - **OASPL** at $\theta = 140^\circ$ angle (sweeping)
  - chord curvature constraint $\frac{d^2c}{dr^2} < 0$

Difficult to get optimality criteria for the propeller+wing case



Not much difference between chord distributions



Conclusions & Next Steps

- Conclusions
  - Got some propeller+wing optimizations to converge, with acoustic constraints!
  - Tip #1: increased finite core length helps unsteady VLM derivatives
  - Tip #2: chord concavity constraint $\frac{d^2c}{dr^2} < 0$ helps optimizations
- Next steps
  - What's going wrong with the propeller+wing case optimality? Numerical issues with the derivatives? Interpolation problems?
  - Structural model

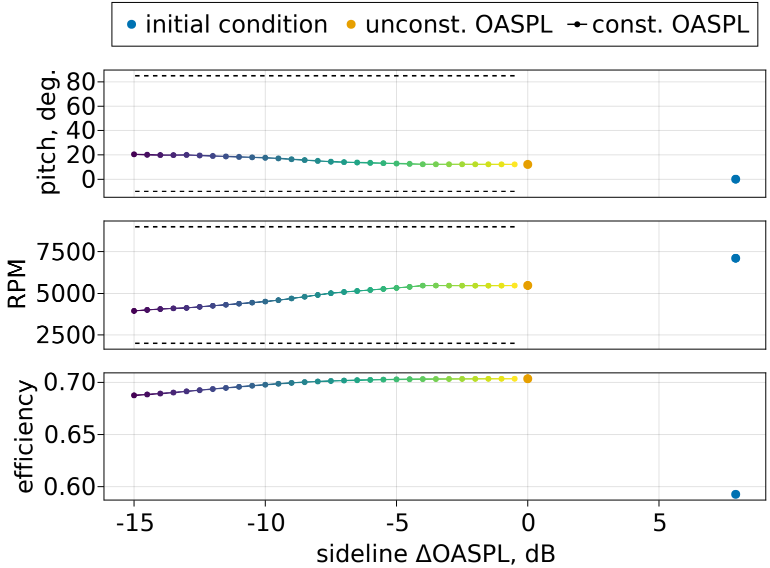
Thanks!

Thank you to:

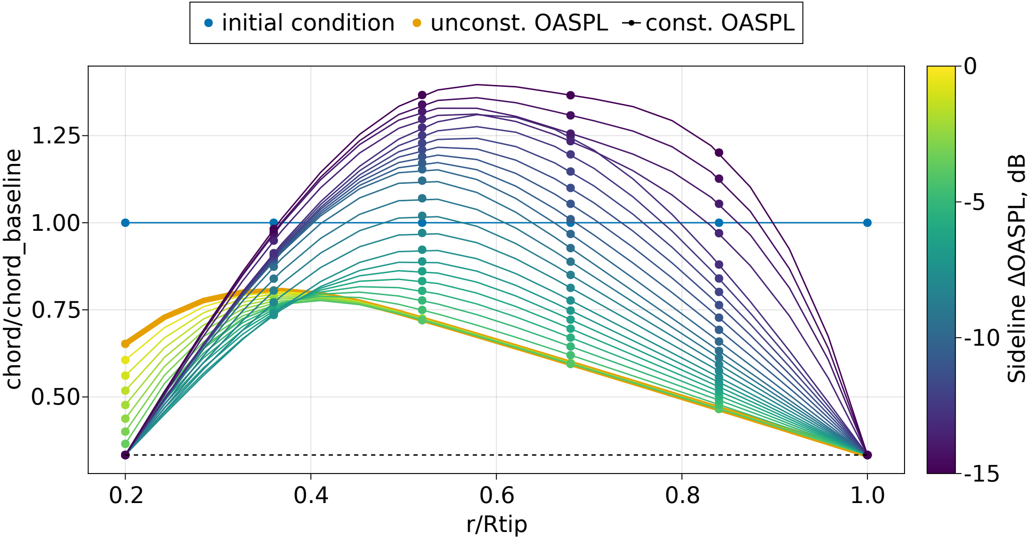
- **Taylor McDonnell**, Andrew Ning from BYU.
- NASA Glenn RVLT Acoustics Branch team, esp. Chris Miller.
- Nik Zawodny, Len Lopes from NASA Langley.
- Justin Gray and the Aviary Group at NASA Glenn.
- NASA Transformational Tools & Technologies Project

Isolated Propeller Results

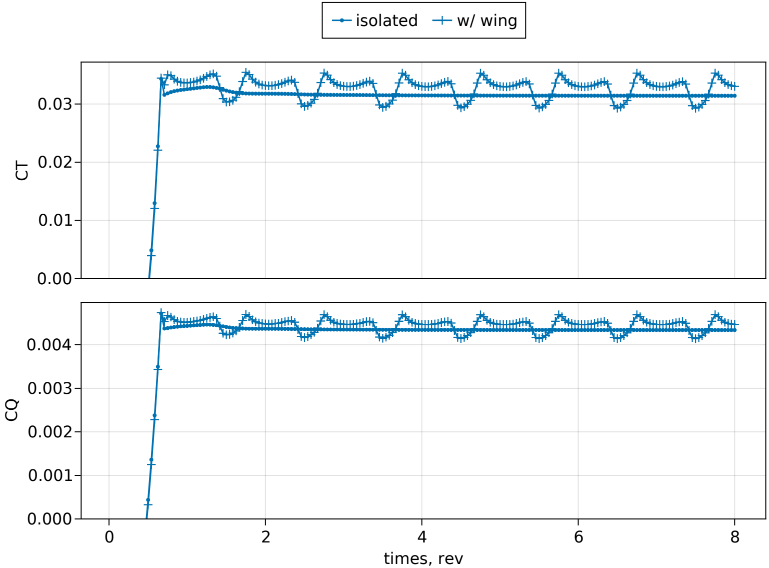
Less RPM + more collective = quiet propeller



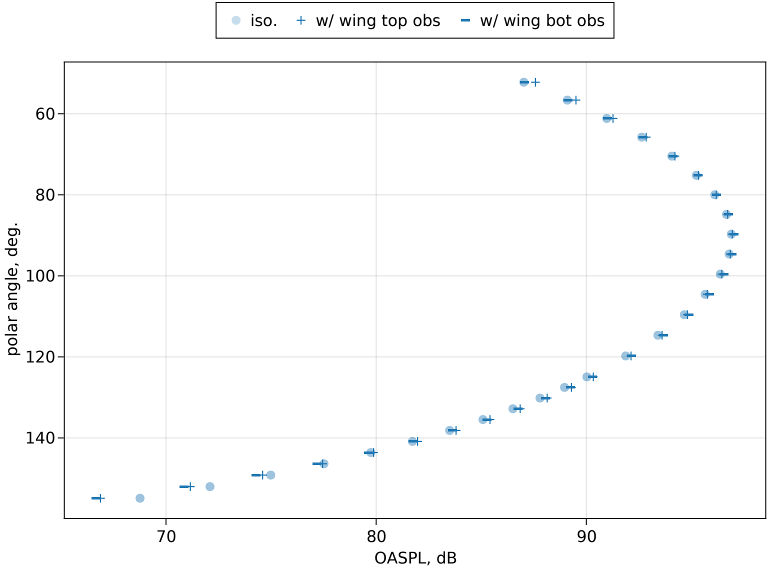
Need more chord to maintain thrust constraint



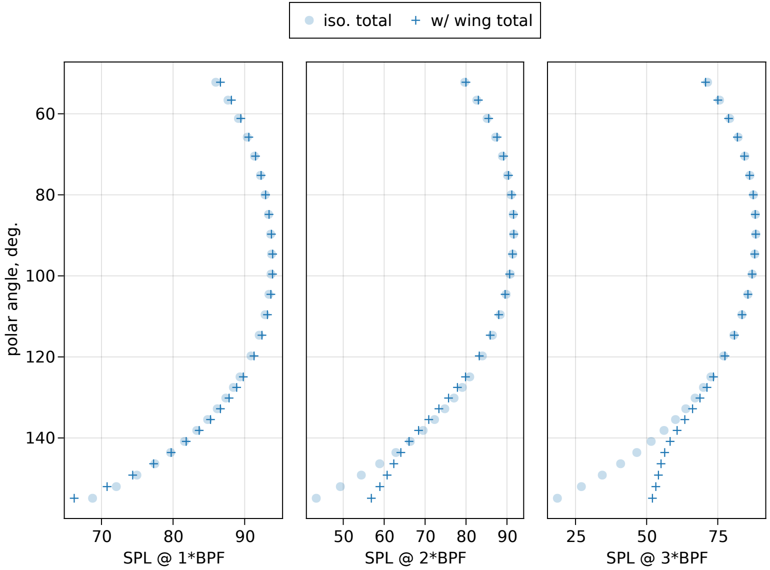
Wing clearly influences thrust and torque time histories



Wing causes slight change in OASPL, azimuthal asymmetry



Wing's effect seen in higher BPF harmonics



Wing increases loading noise, not thickness noise